

Geiger Mode Avalanche Photodiode (G-APD) with avalanche self-quenching behavior.

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Abstract

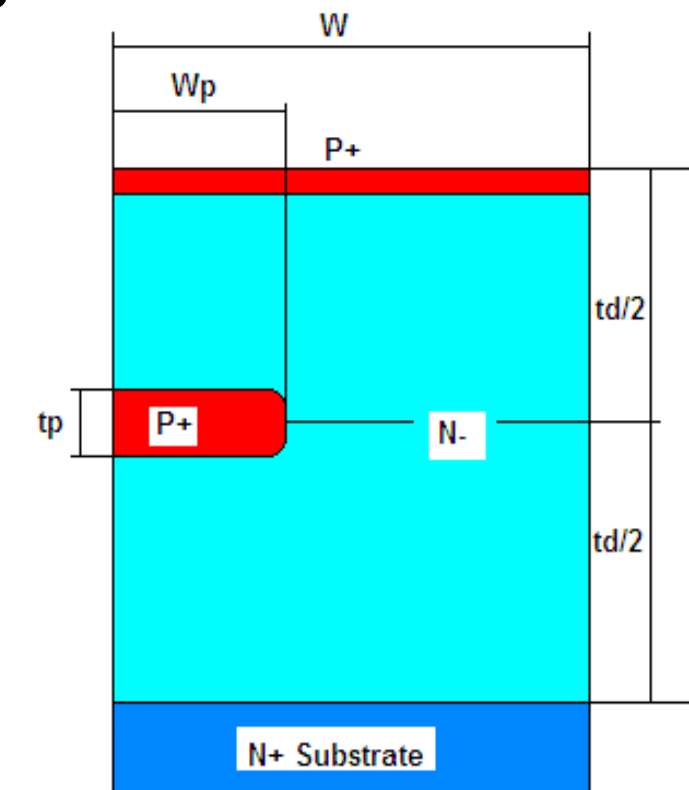
Geiger mode Multipixel Avalanche Photodiode (MAPD) cell simulation study was performed. Transient current waveforms corresponding single photon event upset was obtained in case of conventional APD and floating P-well APD cell. Results indicates advantages of P-welled APD cell in comparison with conventional structure. APD cell avalanche self-quenching phenomenon simulation was demonstrated for the first time. A combination of the self-quenching behavior with bipolar transistor seems to be beneficial for a new device generation and is under evaluation now.

Motivation

The one of the most important devices used in optical communication systems and medical imaging systems are Avalanche Photo Diodes (APDs). APDs are the proper devices in signal detection because of their wide bandwidth, low noise operation and sensitive detection respect to other detectors. The operation principle of an APDs is based on the conversion of the energy of photons (gamma-quanta, ionizing particles) into free charge carriers in the semiconductor bulk and their further multiplication with impact ionization. APDs operated at a breakdown voltage or slightly above, called the Geiger mode (G-APD). G-APD enables a single optical-photon sensitivity with sub-nanosecond timing characteristics. Used in this Geiger mode, the APD pixels are capable of counting single photons events. Self-propagating avalanche would cause the diode to conduct enough current to be readout by external circuit. If, however, a circuit element detects the presence of this avalanche current, and subsequently drops the bias below the BV, the self-propagating avalanche will be quenched. After quenching, the bias can then raised again, above breakdown, awaiting the arrival of another single photon event, thereby resetting the G-APD pixel.

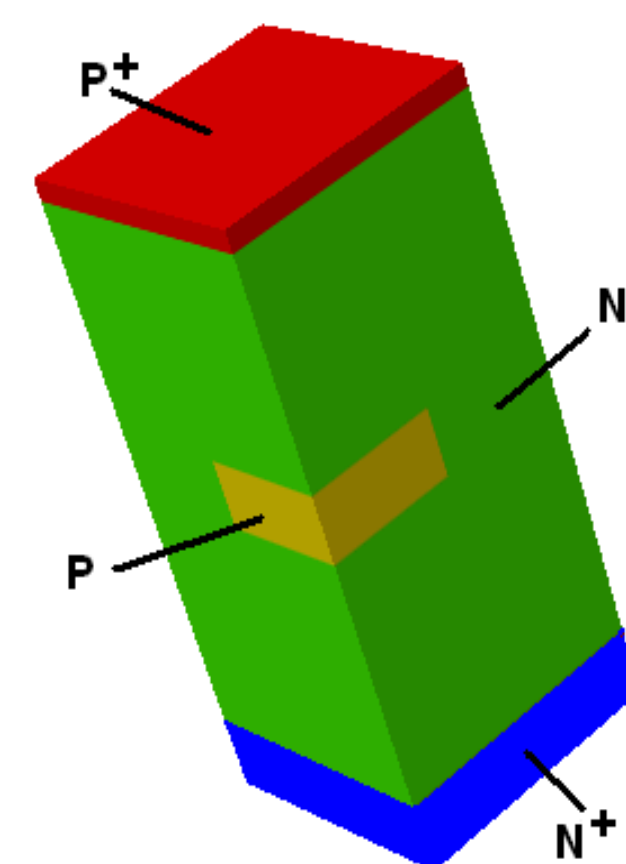
MAPD cell design

Structure has N⁻ region thickness 8 μm . Upper contact P⁺ layer is shallow with junction depth $X_j=0.3 \mu\text{m}$. Shallow upper layer improves blue light sensitivity. Floating P-well placed at the middle of N⁻ region and manufactured with subsequent epitaxial, implantation and drive-in steps. Final floating P-well thickness after doping drive-in is about 1 μm .

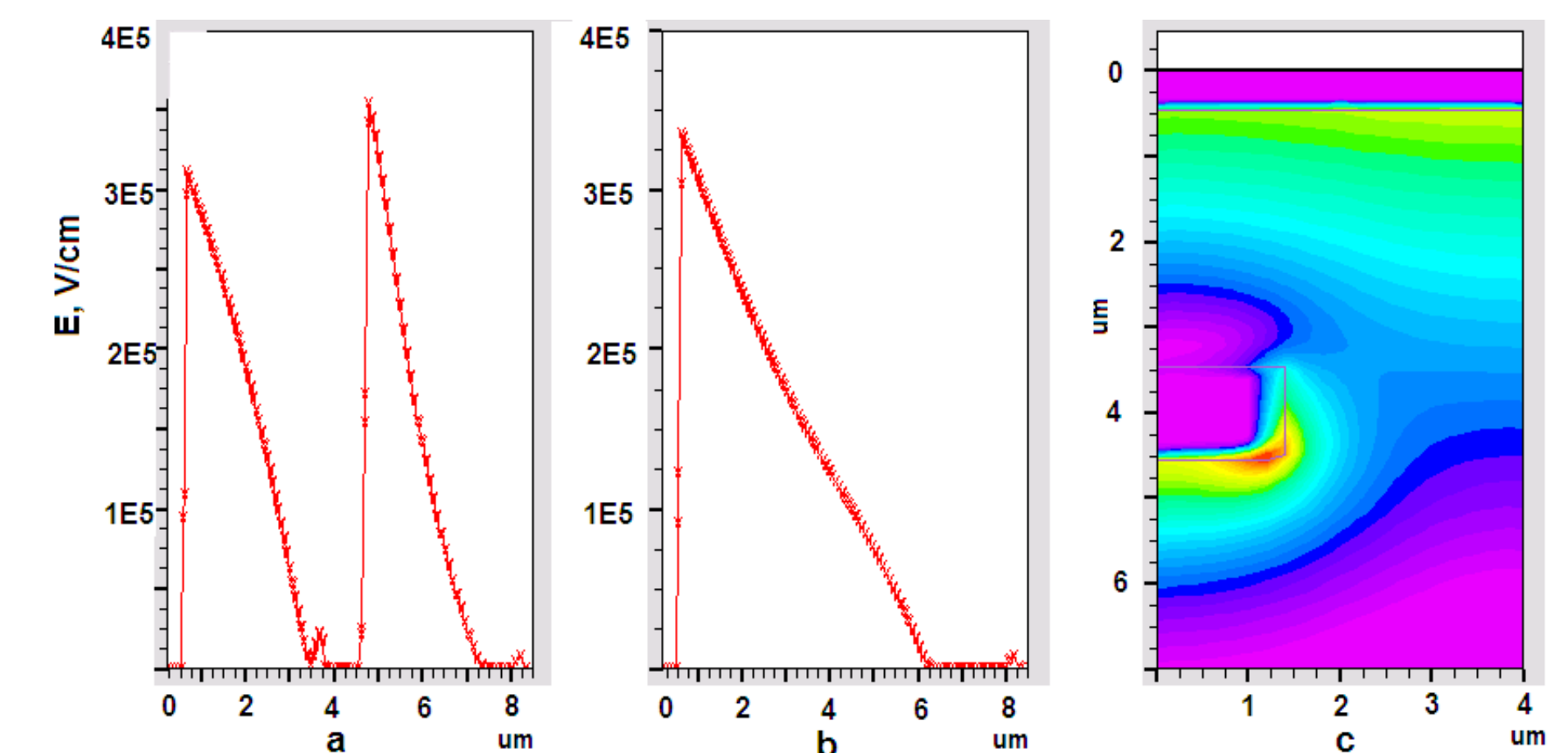


P-welled MAPD 3-D structure size is 4x4x9 μm
Floating P+ width $W_p=1-2 \mu\text{m}$
Floating P+ thickness $t_p=1 \mu\text{m}$
Floating P+ Boron dose $D_a=1E12-3E13 \text{ cm}^{-2}$
N- region thickness $t_d=8 \mu\text{m}$
N- phosphorus doping $N_d=1E14-1E16 \text{ cm}^{-3}$

Regular MAPD 3-D structure size is 4x4x9 μm
N- region thickness $t_d=8 \mu\text{m}$
N- phosphorus doping $N_d=1E14-1E16 \text{ cm}^{-3}$



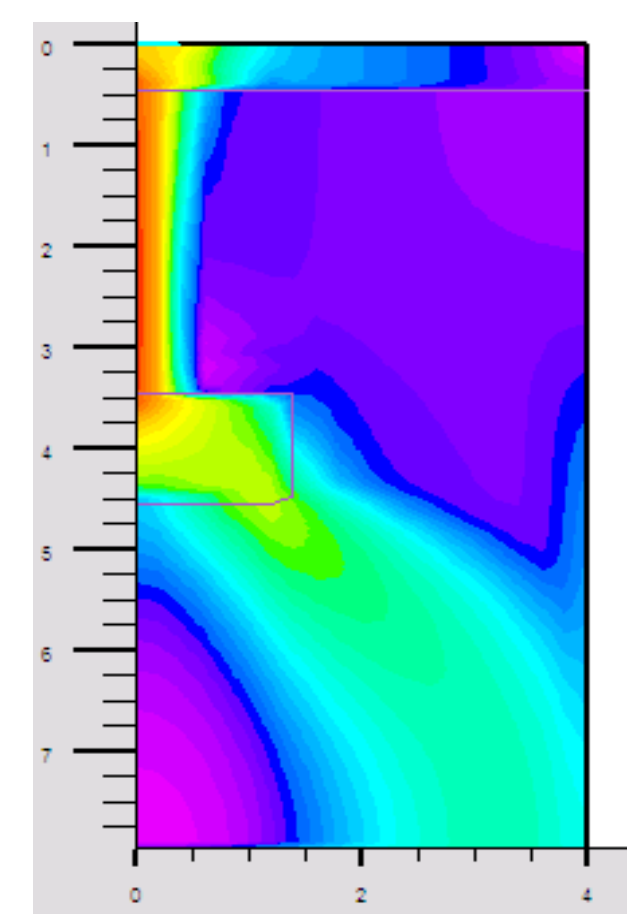
DC Simulation



Field strength distribution for P-welled APD at $U=94 \text{ V}$:

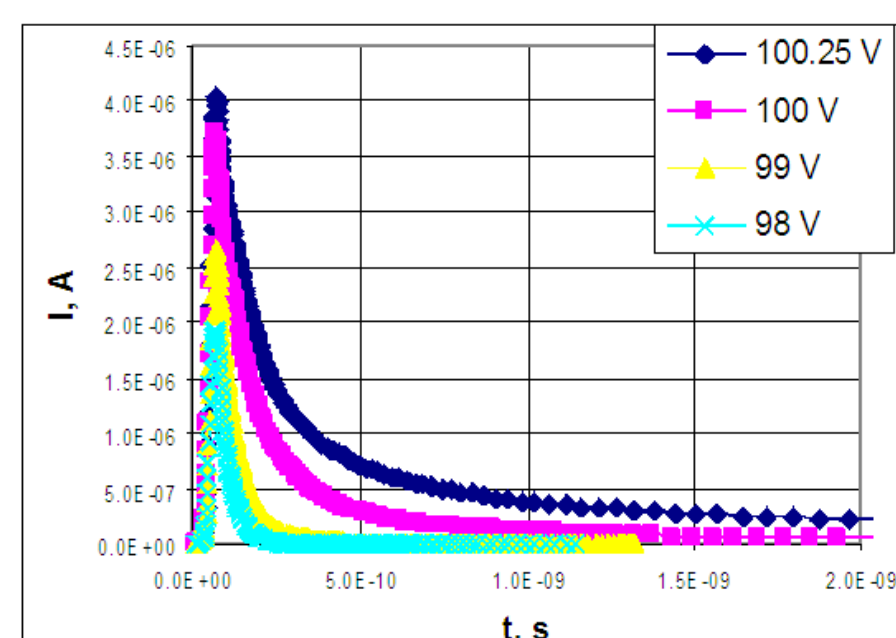
- a) Cross section at $x=0 \mu\text{m}$
- b) Cross section at $x=4 \mu\text{m}$
- c) 2D distribution.

Leakage current distribution for P-welled APD at $U=94 \text{ V}$. Leakage current path more or less corresponds to the avalanche current path.

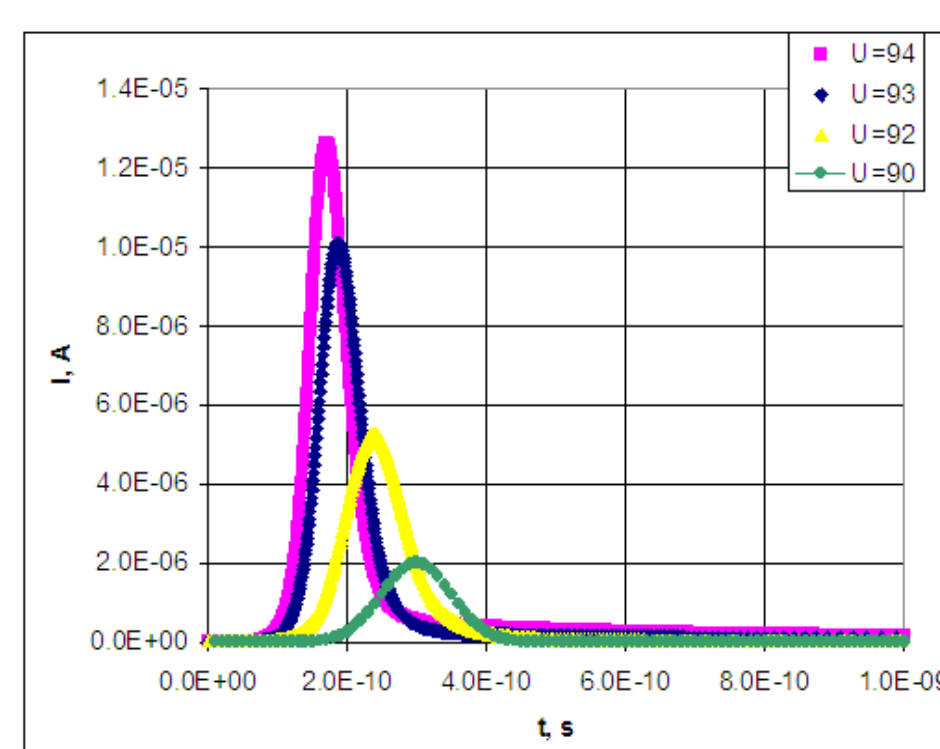


Single Photon Event Transient Time Simulation

For the estimations APD multiplication factor M and current pulse waveform transient time simulation was performed for both structures. Temperature conditions are isothermal at $T=300\text{K}$. After applying reverse bias voltage, transient time simulation was done. Single photon event upset was simulated as electron-hole pair generation at the p-n junction vicinity. Following avalanche-generation of carriers and their current was further simulated.

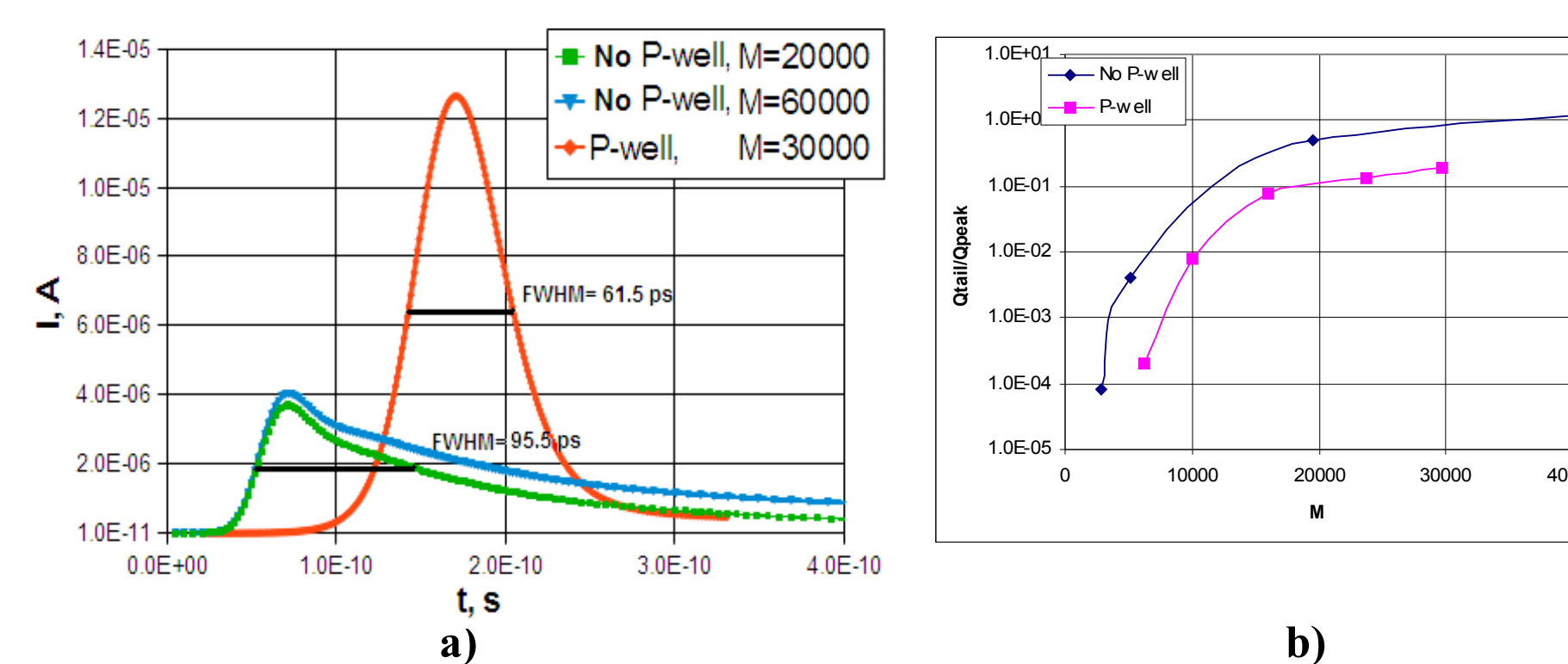


Avalanche current waveforms for the no P-well cell.



Avalanche current waveforms for the P-well cell. Avalanche self-quenching behavior can be seen as peak current shifts towards shorter time.

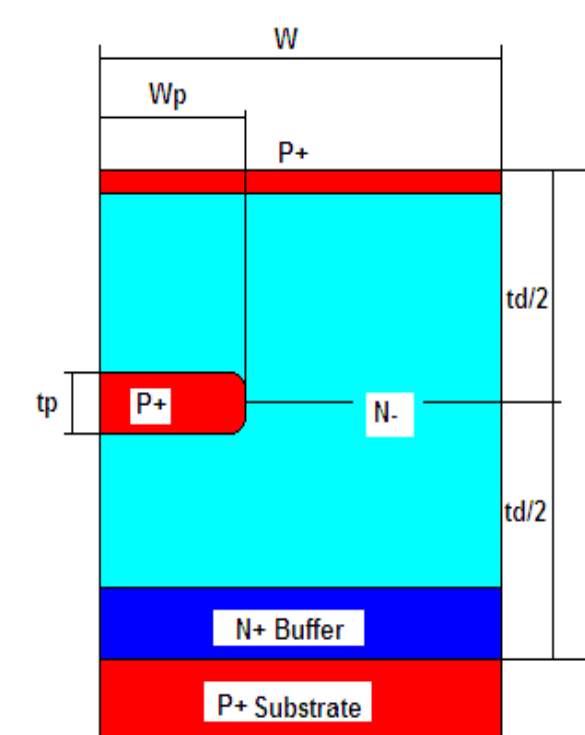
Discussion



Single photon event pulse shape comparison (a). Current pulse Full Width at Half Maximum (FWHM) is 30-40% less for a P-welled APD with a comparable multiplication factor M .

Current pulse tailing (b). For the current tailing estimation purposes, generated charge was splitted into two parts:
 Q_{peak} at $t < 0.5 \text{ ns}$ and Q_{tail} at $t > 0.5 \text{ ns}$
 Q_{tail}/Q_{peak} ratio was plotted as a function of multiplication factor M (Fig. b). Given ratio allow to compare P-welled and non P-welled structure s in terms of pulse duration and recovery time.
P-welled structure have less tailing in factor of 7-8 as compared with non P-welled structures.

Unique avalanche self-quenching behavior makes possible further device development. Switching substrate type from N⁺ type to the P⁺ type turns device to the photo-transistor. Floating P-well improves avalanche ruggedness for such kind of transistor and allows operation at avalanche conditions. Currently avalanche photo-transistor is under simulation study.



Conclusions

Geiger mode Multipixel Avalanche Photodiode (MAPD) cell simulation study was performed. Transient current waveforms corresponded single photon event upset was obtained in case of conventional APD and floating P-well APD cell. Results indicate advantages of P-welled APD cell in comparison with conventional structure. Current pulse FWHM was reduced in factor of two at the multiplication factor $M=30000$. At the same conditions current tailing was reduced in factor of eight. A floating P-well APD cell demonstrates an outstanding time resolution characteristics for single photon detectors.

APD cell avalanche self-quenching phenomenon simulation was demonstrated for the first time. A combination of the self-quenching behavior with bipolar transistor seems to be beneficial for a new device generation and is under evaluation now.

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